Purdue University

Purdue e-Pubs

International Compressor Engineering Conference

School of Mechanical Engineering

2006

Development of a Two-Dimensional Finite Element Model of a Suction Valve for Reduction of Pressure Pulsation in the Suction Manifold of a Multi-Cylinder Automotive Compressor

Jeongil Park
Samsung Electronics Co.

Nasir Bilal
Purdue University

Douglas E. Adams
Purdue University

Development of a Two-Dimensional Finite Element Model of a Suction Valve for Reduction of Pressure Pulsation in the Suction Manifold of a Multi-Cylinder Automotive Compressor

Jeong Il PARK[1], *Nasir BILAL[2], Douglas E. ADAMS[2]

[1]Senior Engineer, Digital Appliance R & D Group
Samsung Electronics Co., LTD, Korea
E-mail: jijyse.park@samsung.com

[2, 3] Purdue University, School of Mechanical Engineering
140 S. Intramural Drive, Ray W. Herrick Laboratories
West Lafayette, IN 47907-2031, USA
Telephone: (765)496-6033; Fax: (765)494-0787
[2] bilal@ecn.purdue.edu, [3] deadams@ecn.purdue.edu

ABSTRACT

This study uses a two-dimensional finite element model of the suction valve for a multi-cylinder automotive compressor to identify the mass flow rate through the valve. The forced pressure responses in a simplified cylindrical annular suction cavity with area changes are then obtained using the calculated mass flow rate in conjunction with linear acoustic theory and a four pole parameter formulation. The estimated pressure pulsations are compared with the pressure pulsations obtained from experiments. It is shown that the simulation results are in good agreement with the experimental results. It is concluded that a two dimensional finite element model is advantageous to consider various geometries of the valve without the simplifications required in a one-dimensional or single-degree-of-freedom valve model, and that the two-dimensional model also provides better results for the pressure pulsations in the suction manifold.

1. INTRODUCTION

This research focuses on the development of a two-dimensional (2D) Finite Element Model (FEM) of a reed valve used in the suction port of a multi-cylinder, variable stroke, automotive compressor. It is an extension of the study 'Mathematical Modeling and Simulation of a Multi-Cylinder Automotive Compressor' (Park, 2004a), where a complete simulation model for multi-cylinder automotive compressor was developed to investigate the pressure pulsations in the suction manifold using a one-dimensional (1D) valve model. Correct understanding of the valve dynamics is extremely important as the overall performance of a reciprocating compressor is highly dependent on the valve response. Valve vibration disturbs the refrigerant flow and generates pressure fluctuations in the suction manifold. In calculating the gas pulsations, the critical step is to calculate the mass flow rate through the valve. In the earlier study (Park, 2004a), the reed valve was modeled as a one-dimensional beam using a Bernoulli-Euler linear differential beam equation (Park, 2004b). However, the problem with such a beam model is that several approximations have to be used to incorporate the effects of valve geometry and the force distribution.

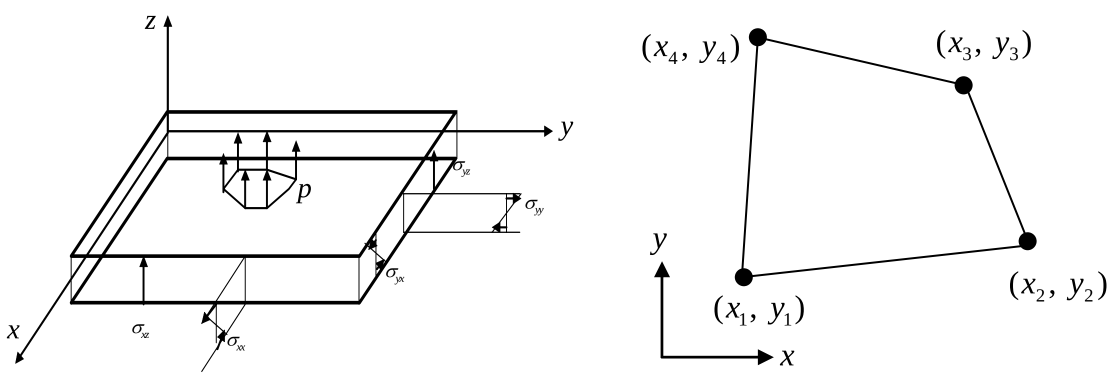
In this paper, a two-dimensional reed valve is modeled as a thin plate using FEM. The advantages of a two-dimensional model are that it can better predict the valve response for any valve geometry without using modeling approximations and also that different pressure distributions can be applied to the valve without much approximation to determine an optimal valve design.

2. MODELING DETAILS

The two-dimensional FEM valve model was formulated using plate elements (Rao, 2005). Plate element equations were derived using classical theory of thin plates under the following assumptions:

a) the thickness of the plate is small compared to its other dimensions,
b) deflections are small,
c) the middle plane of the plate does not undergo in-plane deformation, and
d) transverse shear deformation is zero.

The stresses induced in an element of a plate are shear stresses σ_{xz}, σ_{yz}, and σ_{y} and normal stresses σ_{xx} and σ_{yy} as shown in Fig. 1 (a).



(a) (b)

Figure 1: (a) Stress acting in a plate element and (b) a plate element modeled as a 4-node quadrilateral.

A four node quadrilateral element with 3-degrees-of-freedom per node was assumed as shown in Fig 1(b). Using standard FEM methodology (Rao, 2005), the stiffness, mass, and load vector matrices were derived. Element matrices and vectors were assembled and the overall equation of motion for the system was obtained. By assembling the element matrices and vectors, the desired dynamic equation of motion of the structure can be written as

$$[M]\{\ddot{q}'\} + [K]\{q'\} = [F] \tag{1}$$

where $\{\ddot{q}'\}$ is the vector of nodal accelerations in the global system, [M] is the global mass matrix, [K] is the global stiffness matrix, and [F] is the total load vector. The equations of motion were solved by applying the boundary and initial conditions using Newmark's method (Logan, 1997).

3. METHODOLOGY

In developing the FEM simulation model, the FEM modeling package ANSYS was first used to idealize the structure into N number of finite elements and then elemental and nodal information was extracted from ANSYS. This nodal and elemental information was used to form the system mass, stiffness and force matrices according to the FEM theory explained above (Kwon, 2000). The main motivation to develop the FEM code in Matlab® for the valve rather than using any commercial software was to make it easy to combine the current 2D valve code with the previous code for the other components and processes of the compressor, which was used to calculate the gas pulsations. The time independent boundary condition used at the end of the valve was considered as clamped and is shown in Fig. 3. The equations of motion were numerically integrated using Newmark's method.

The complete compressor model consisted of sub models of compression cycles based on first law of thermodynamics, dynamics of the suction valve, and mass flow rate equations for the valve ports. The forced pressure responses in the simplified cylindrical annular suction cavity with area changes was then obtained using the calculated mass flow rate in conjunction with linear acoustic theory and a four pole parameter formulation. The simulation procedure used here was based on the pervious study (Park, 2004a), where only the suction valve model was replaced by a 2D FEM valve model. The entire simulation procedure is explained below in the flow chart in Fig. 2.

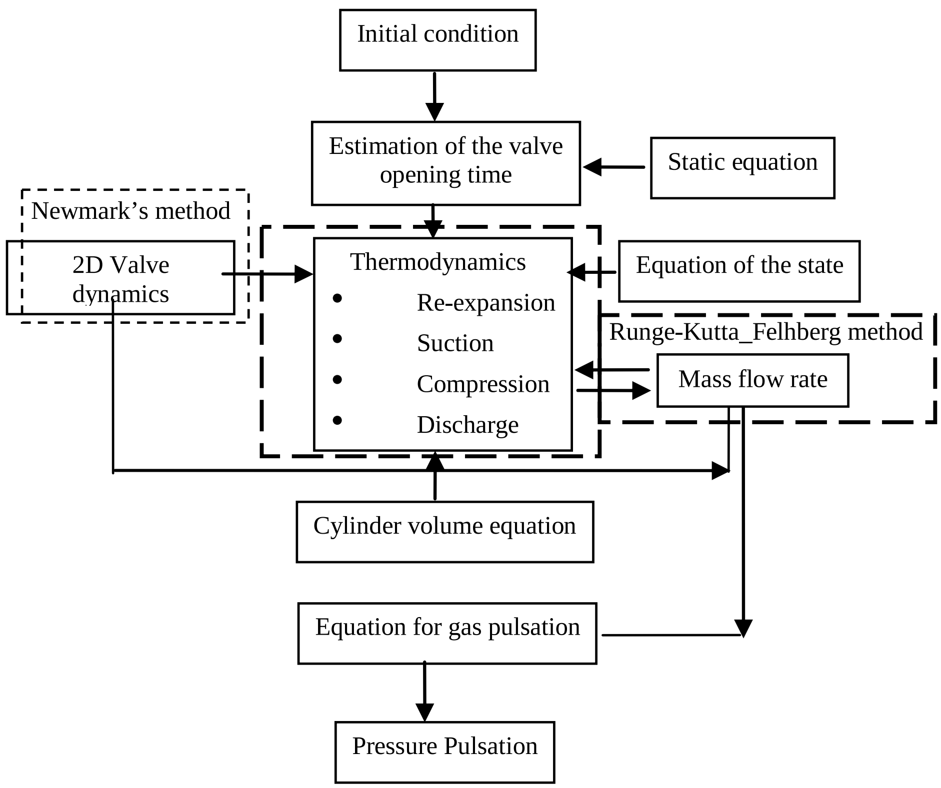


Figure 2: Simulation flow chart

4. VALIDATION OF A TWO-DIMENSIONAL FEM MODEL

To validate the 2D valve model, first the natural frequencies of the reed valve shown below in Fig. 3 were computed using the finite simulation code in Matlab® and compared with those obtained from ANSYS. The results of the two models matched very closely and are shown below in Table 1.

Table 1: Natural Frequencies of the 2D reed valve

Mode	ANSYS	MATLAB	Error (%)
1	245.58	246.86	0.52
2	1510.7	1515.9	.34
3	1701.1	1703.2	0.01
4	4636.7	4661.4	0.53
5	4747.3	4747.3	0

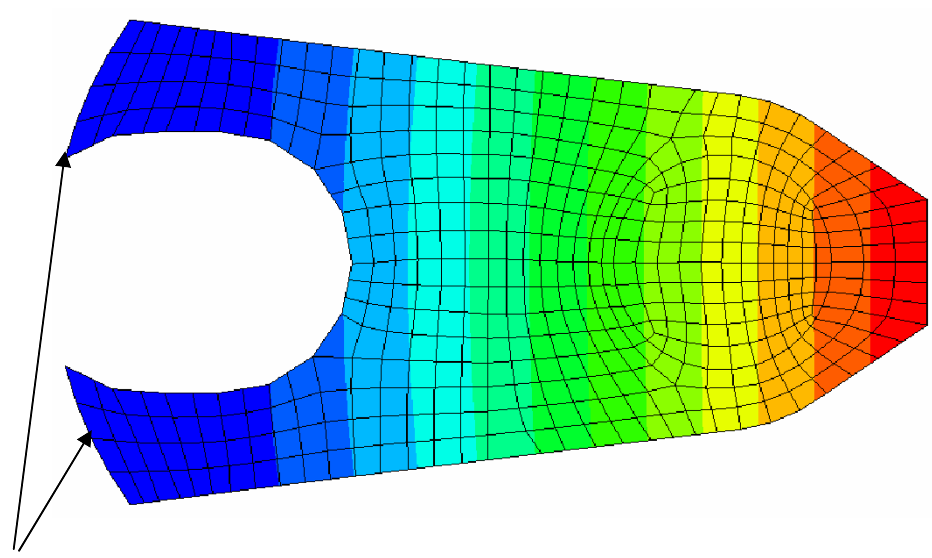


Figure 3: The FEM model of reed valve

Secondly, the static deflections of the 2D FEM valve model were computed using Matlab and compared to those from the ANSYS. The two deflections also matched very closely.

5. SIMULATION RESULTS

In order to investigate the validation of the simulation models, four different operating conditions were selected as shown in Table 2. Using the mass flow rates calculated, the pressure pulsations were calculated along the circumferential direction of the annular cavity near the first set of natural frequencies. A comparison of analytical and experimental results for 1D and 2D cases is shown in Fig. 4 and Fig. 5. The results for the 2D case slightly over predict the gas pulsation. The reason is that in the current 2D valve model, the effect of the dynamic fluid drag surrounding the valve has not been considered.

Table 2: Operating conditions for compressor

Operating Conditions					
		Suction		Discharge	
Q [kg/h]	*rpm*	P_s (static) [kPa abs]	T_s [℃]	P_d (static) [kPa abs]	T_d [℃]
50	1500	293.0	14.4	916.0	56.0
70		193.0	9.3	932.0	52.2
70	2000	291.0	25.6	922.0	62.2
90		291.0	14.6	924.0	60.0

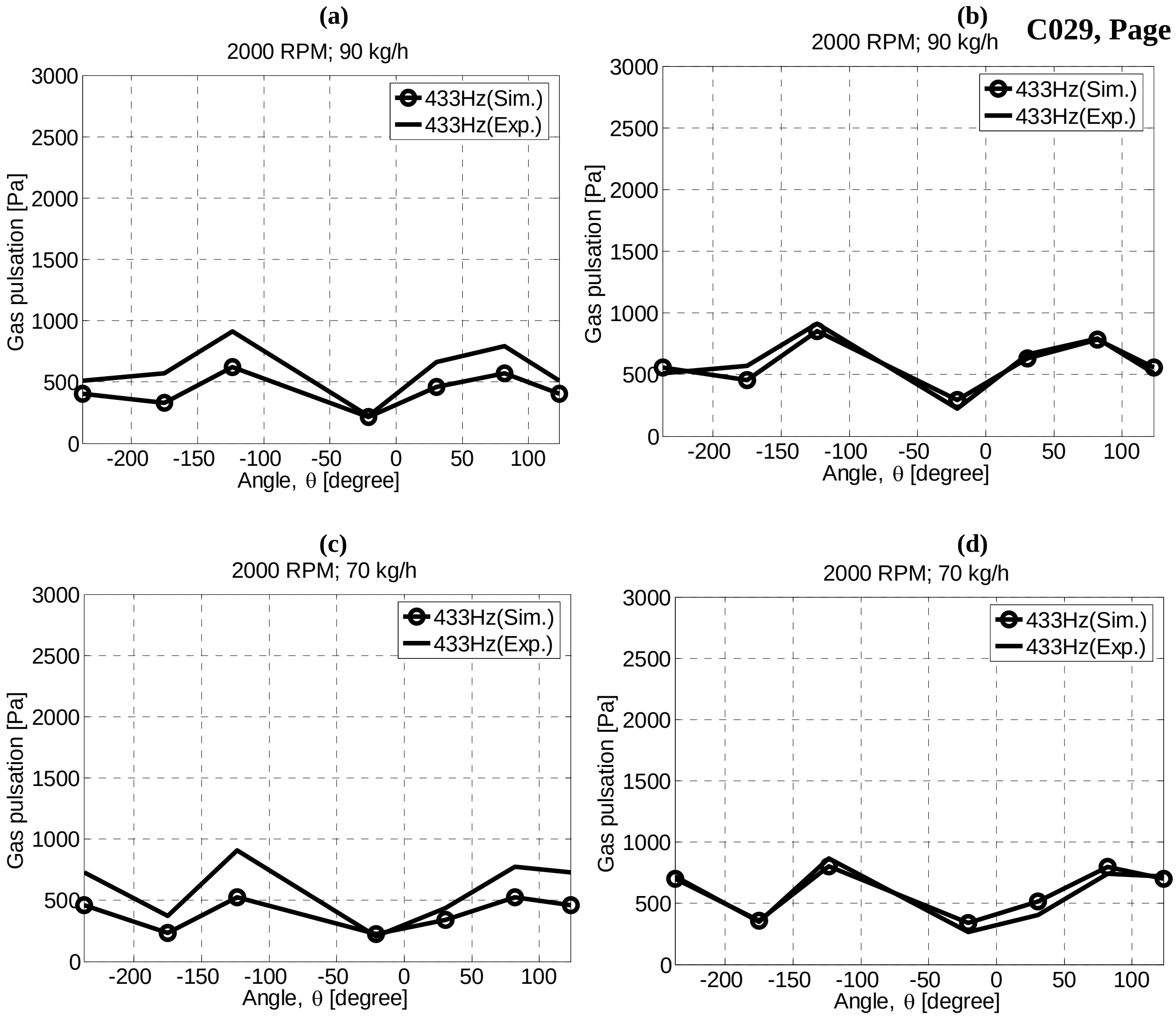


Figure 4: (a) Gas Pulsation (2D: 2000 rpm, 90 Kg/h); (b) Gas Pulsation (1D: 2000 rpm, 90 kg/h); (c) Gas Pulsation (2D: 2000 rpm, 70 Kg/h; (d) Gas Pulsation (1D: 2000 rpm , 70 kg/h)

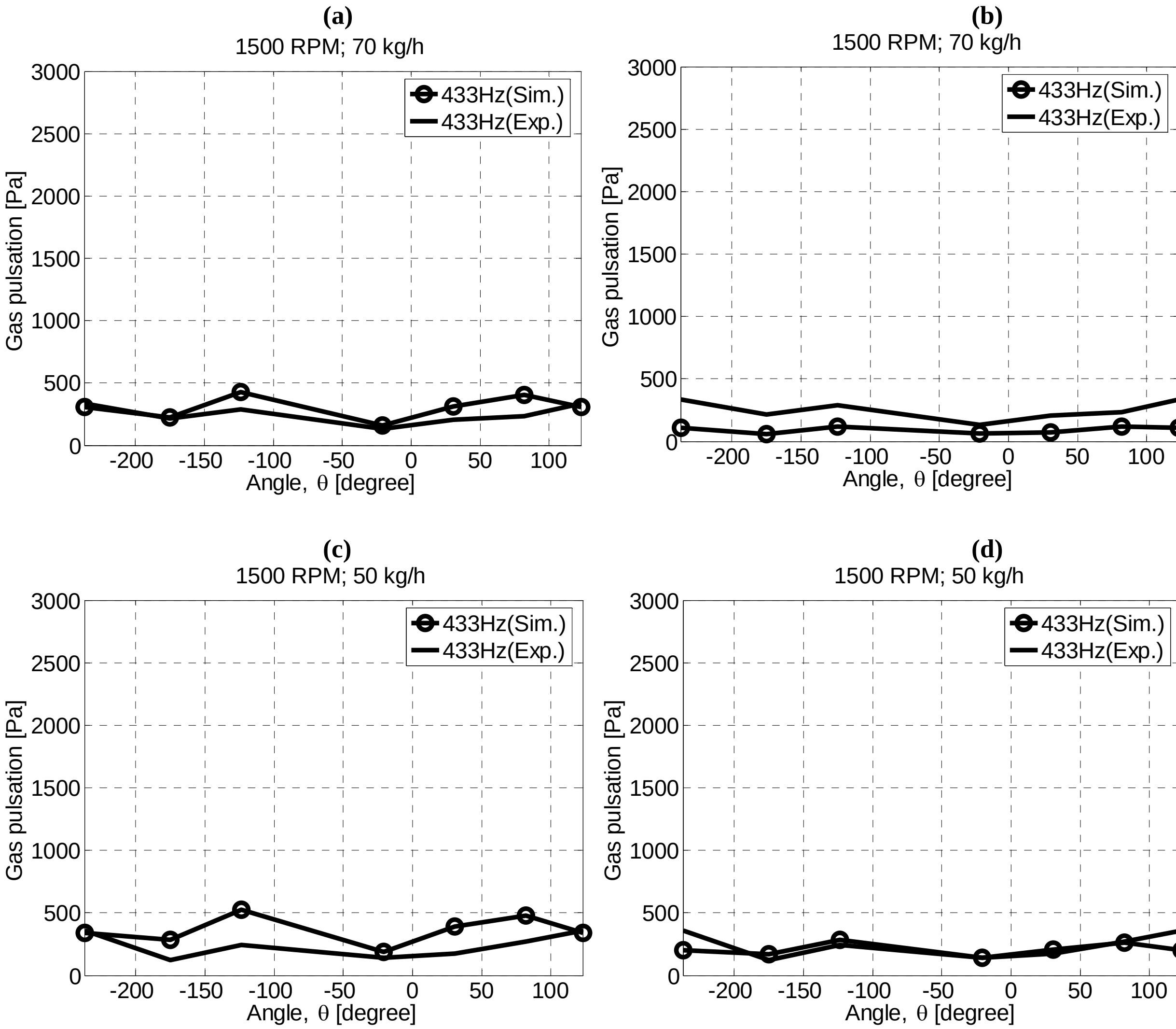


Figure 5: (a) Gas Pulsation (2D: 1500 rpm, 70 Kg/h); (b) Gas Pulsation (1D: 1500 rpm, 70 kg/h); (c) Gas Pulsation (2D: 1500 rpm, 50 Kg/h; (d) Gas Pulsation (1D: 1500 rpm , 50 kg/h)

6. CONCLUSIONS

In this simulation, a 2D FEM valve model was used to calculate the gas pulsation in the suction manifold using the calculated mass flow rate in the valve port. The following remarks have been concluded:

- The pressure drop at the outer part of the suction port has not been considered and therefore it is assumed that the pressure drop is only dependent on the pressure difference between pressure in the suction manifold and that in the cylinder. Also the effect of the fluid damping on the suction valve has not been considered. It is believed that including these two effects could correct the difference between the gas pulsations of analytical and experimental results.
- Using the 2D valve model, any valve geometry can be considered.
- Any pressure distribution could be used without much approximation.
- Further studies aimed at considering the above mentioned factors and looking at different valve geometries are currently under way.

REFERENCES

1. Kwon, Y. W., Bang, H., 2000, *The Finite Element Method using MATLAB*, CRC Press.
2. Logan, D. L., 1997, *A First Course in the Finite Element Method using Algor*, PWS Publishing Company.
3. Park, J., Adams, D. E., 2004, Numerical and Experimental Studies of Gas Pulsations in the Suction Manifold of a Multi-Cylinder Automotive Compressor, submitted for review to *Trans. ASME J. Vibration and Acoustics*.
4. Park, J., 2004, *Mathematical Modeling and Simulation of a Multi-Cylinder Automotive Compressor*, PhD Thesis, Purdue University.
5. Park, J., Adams, D. E., 2005, Gas Pulsation Reductions in a Multi-Cylinder Compressor Suction Manifold using Valve-to-Valve Mass Flow Rate Phase Shifts, submitted for review to *Trans. ASME J. Vibration and Acoustics*.
6. Rao, S. S., 2005, The Finite Element Method in Engineering, Elsevier Inc.